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SHOCK COMPRESSION MEASUREMENTS AT PRESSURES GREATER THAN 1 TPa*

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ABSTRACT

We have obtained precise Hugoniot data for samples of aluminum, quartz, iron, molybdenum, and low-density molybdenum (ρ_o=8.29 g-cm^{-3}) using the impedance-matching technique. An underground nuclear explosion drove a nearly planar, 5-TPa shock into a molybdenum standard. Shock velocities were measured with 1.5% to 2.5% accuracies.

INTRODUCTION

The pressure range accessible using conventional dynamic impact experiments[1] has been limited to <1 TPa. We have developed techniques[2-3] using underground nuclear explosives for obtaining precise equation-of-state (EOS) data at pressures approaching 10 TPa. An earlier absolute measurement[2] for molybdenum at 2.0 TPa provided increased confidence in its calculated EOS[4]; a follow-on impedance-matching experiment[3] for uranium at 6.7 TPa stimulated improved theoretical treatments[5] for both uranium and the molybdenum standard. In the present experiment,[6] we used the same shock-production technique to obtain Hugoniot data for 13 samples relative to molybdenum.

EXPERIMENT AND RESULTS

A nearly planar shock was produced in a molybdenum standard located on top of a lead base plate ~3 m from the nuclear explosive. The shock passed into seven stacks of sample materials positioned as shown in Fig. 1. Extensive shielding reduced the calculated neutron and gamma radiations at the samples to a level that produced a temperature rise of ~10K. Shock arrival times were determined using an array of 75 electrical contact pins[3] separated by 1 to 3 mm in the vertical (z) direction; horizontal positions (x-y plane) were chosen to avoid rarefactions assuming a release angle of 35° at discontinuities. Five pins were multiplexed per cable, and different decay times provided a unique signature pulse for each pin. The signal from each cable was recorded along with a 100-MHz time base on a set of oscilloscopes that provided coverage for 2 to 3 μs. For 25 of the pins, the signal quality was excellent, and shock-arrival times were determined with ±1-ns uncertainties. The remaining pins produced lower quality signals and uncertainties of 3 to 10 ns were assigned to the closure times.

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DATA ANALYSIS AND CONCLUSIONS

The data analysis procedure involved several hundred least squares fits of the function $t = t(x,y,z)$ to the pin coordinates and closure times using functional forms for t that included either r or $r^2 (= x^2 + y^2)$ dependence. These fits indicated that the shock velocity was decreasing slightly with z and that the shock front was curved with an effective radius of curvature ≈2 m. Additional fits indicated that nonplanar effects were purely radial and that asymmetry about the z-axis introduced <6-ns variation in arrival time along a radius.

Various subsets of the pins were used to fit different portions of the shock front; this procedure was supported by an analysis of preliminary global fits. All fits gave small values (consistent with zero) for the decrease in the shock velocities. In the previous 6.7-TPa experiment,[3] the shock velocities changed by <1% over 10 mm; therefore, we assumed a similar 1% decrease across the samples in this experiment with the average (center) velocity determined from the fits. The resulting shock velocities corresponding to ±0.5% variations at the lower and upper surface are summarized in Table I. For the molybdenum standard, an overall uncertainity of 1.5% was assigned to the measured upper surface value of 27.16 km/s. For the small samples (except iron), the shock-velocity errors from the fits were ∿1%; overall uncertainties of ±2% were assigned to each of these velocities to include systematic effects. For the iron sample, an uncertainty of ±2.5% was assigned to the measured shock velocity.

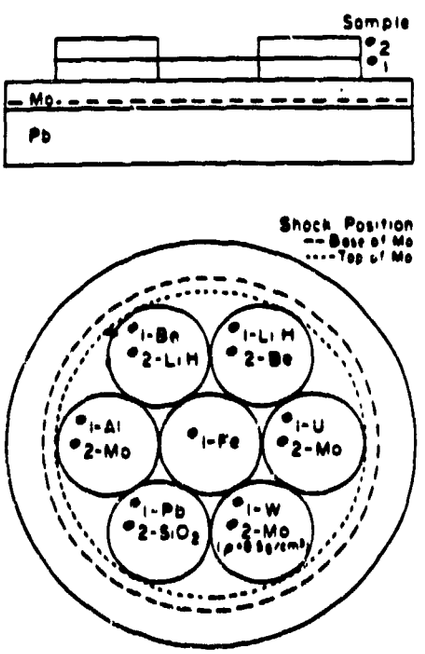

Fig. 1. Schematic drawing of the sample package showing the 180-mm-diam by 12-mm-thick molybdenum standard, the 25-mm-thick lead driver, and the thirteen 10-mm-thick samples, which consisted of the indicated materials.

The interface velocities were used to obtain Hugoniot points from impedance-matching analyses for each possible pair of samples. For the lower samples, the measured velocity at the upper surface of the molybdenum standard was used in the analysis. For each upper sample, the corresponding lower sample was treated as the standard material. For the molybdenum atop the aluminum, the measured shock velocity at the upper aluminum surface was used to determine a Hugoniot point. For the quartz and low-density molybdenum, the initial state in the

Table I. Comparison of Experimental and Calculated Results

Material	Shock Velocity (km/s) Experiment[b]	Difference[c](%) Old[d]	New[d]	Hugoniot Point[a] Pressure (TPa)	Particle Velocity (km/s)
Mo Std	27.16*	---	---	4.900(3.5)	17.67(2.0)
Al	34.39*	1.63	0.55	2.226(3.8)	23.89(2.7)
Mo	24.64*	-0.13	1.90	4.034(4.5)	16.05(4.3)
Pb	23.79[e]	---	---	4.723(--)	17.51(--)
Quartz	31.95*	6.66		1.693(4.3)	24.04(3.0)
W	22.12[e]	---	---	6.351(--)	14.87(--)
Mo[f]	24.28*	9.85	9.77	3.693(4.4)	18.35(3.4)
Mo Std	28.02	---	---		
Fe	30.48	-1.92	-3.48	---	---

[a] Based on measured shock velocities and the improved molybdenum EOS; percent errors in parentheses.
[b] Corrected for variation of ±0.5% across each sample: * = upper surface, ' = lower surface. Uncertainties = 1.5 - 2.5% (see text).
[c] $(D_{th}-D_{exp})/D_{exp}$.
[d] Calculated results, "Old" from Ref. 4, "New" from Ref. 5.
[e] Calculated velocity for 1% lower velocity in the Mo standard.
[f] $\rho_o = 8.29$ g-cm^{-3}.

corresponding lower sample was calculated from the pressure in the molybdenum standard. In this calculation, the measured shock velocity of 27.16 km/s was decreased by 1% to account for the decay across the lower sample. These analyses were based on the SESAME EOS library[4] and on both the original and improved[5] molybdenum EOS (when appropriate). The shock velocity in each sample was also calculated using its theoretical EOS; the third and fourth columns of Table I give the percent differences between calculated and experimental values.

For the aluminum-molybdenum pair and the iron sample, differences between calculation and experiment are small with the improved[5] molybdenum EOS giving slightly better agreement. However, the SESAME[4] predictions for these samples using either molydbenum EOS are in good agreement with experiment. For quartz and low-density molybdenum, SESAME-based calculations differ from the measured values by more than the experimental uncertainties.

Table I also gives the experimental Hugoniot points and uncertainties for the samples. The appropriate shock velocities were used to determine the intersection point in the P-u plane of the straight line $P=\rho_o Du$ with the reflected shock (RS) Hugoniot or the release isentrope (RI) of the lower standard material. The initial state of the standard was determined as described above, and the upper-sample results are based on the assumption that SESAME EOSs for the lower samples are correct; the uncertainties correspond to only experimental shock-velocity uncertainties. Both the original[4] and improved[5] EOSs for molybdenum were used in this analysis; however, only the results for the improved[5] molybdenum EOS are given in the table.

The method of the analysis is illustrated in Fig. 2 for the aluminum-molybdenum stack. The regions of interest are shown on expanded scales with theoretical[4,5] Hugoniots shown as heavy curves.

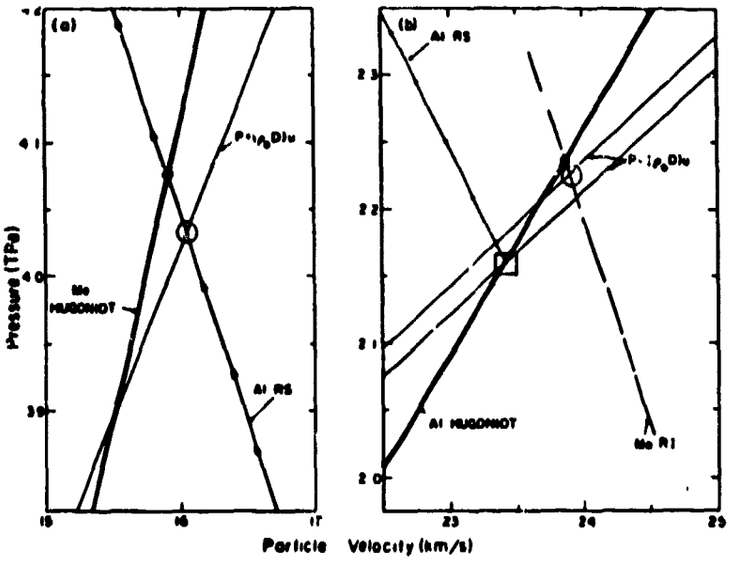

Fig. 2. Plots showing the impedance-matching analysis technique for the alunimum-molybdenum stack. Intersection of the RI or RS Hugoniot (•) with lines labeled $P=\rho_0 Du$ provide experimental points (circled) for Al(b) and Mo(a). Theoretical predictions are indicated by large dots.

This experiment provides Hugoniot data that can be used to check the consistency of theoretical EOS calculations. For aluminum, iron, molybdenum, and lead, calculations based on the SESAME library[4] are in good agreement with these data. Discrepancies for quartz and low-density molybdenum are larger than the experimental uncertainties, indicating the need for improved theoretical treatments.

We plan to field a similar experiment to determine shock velocities with ±0.5% uncertainties for additional sample materials, thereby providing even more stringent tests of theoretical predictions.

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